The Software Package CAOS 7.0: enhanced numerical modelling of astronomical adaptive optics systems

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Abstract The Software Package CAOS (acronym for Code for Adaptive Optics Systems) is a modular scientific package performing end-to-end numerical modelling of astronomical adaptive optics (AO) systems. It is IDL-based and developed within the eponymous CAOS Problem-Solving Environment (CAOS PSE), recently completely re-organized. In this paper we present version 7.0 of the Software Package CAOS, containing a number of enhancements and new modules, in particular for wide-field AO systems modelling.

Adapting to the new CAOS Problem-Solving Environment

The new CAOS PSE [1, 2] has now a unique basic distribution containing its global user interface (the so-called CAOS Application Builder [3]), its library of routines, and a package Utilities where utility modules (to display/save/read data) from the different scientific packages have been merged. The scientific packages developped using this new global version of the CAOS PSE, version 7.0, are presently the Software Package CAOS ([4], see also lagrange.oca.eu/caos) and the Software Package AIRY ([5, 6], see also companion poster [7]). Examples of use of the global user interface of the CAOS PSE together with modules of the Software Package CAOS are shown further on. The list of installed packages (and hence of available modules) appears when pushing pull-down button Modules. The simulation code corresponding to a given designed project simulation is automaticaly generated, at the end of the simulation project design step or at any moment, by pushing pull-down button File. Note that previously developped scientific packages have not been yet adapted to version 7.0 of the CAOS PSE, or will not be at all. For example, the Software Package SPHERE [8] is not developped anymore and would hence have to be used with the previous distribution of the CAOS PSE. At the opposite, the modules that used to compound the (now obsolete) Software Package MAOS (for modelling of multiple-reference and multiconjugate AO systems) have been included within and adapted to this new version of the Software Package CAOS (see next section). The same will occur soon with the modules of the (now obsolete as well) Software Package PAOLAC [9], which modules are a simple embedment of the semi-analytic code PAOLA [10]. Finally note that, together with their specific sets of example projects, the two-only resulting scientific packages AIRY and CAOS are still distributed separately.

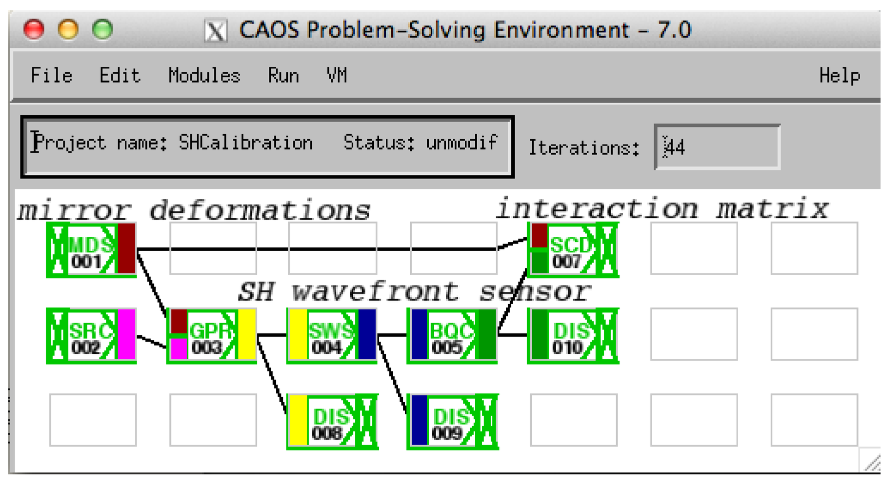
The modules of the new Software Package CAOS

Herafter is a descriptive list of the modules of the Software Package CAOS, version 7.0.

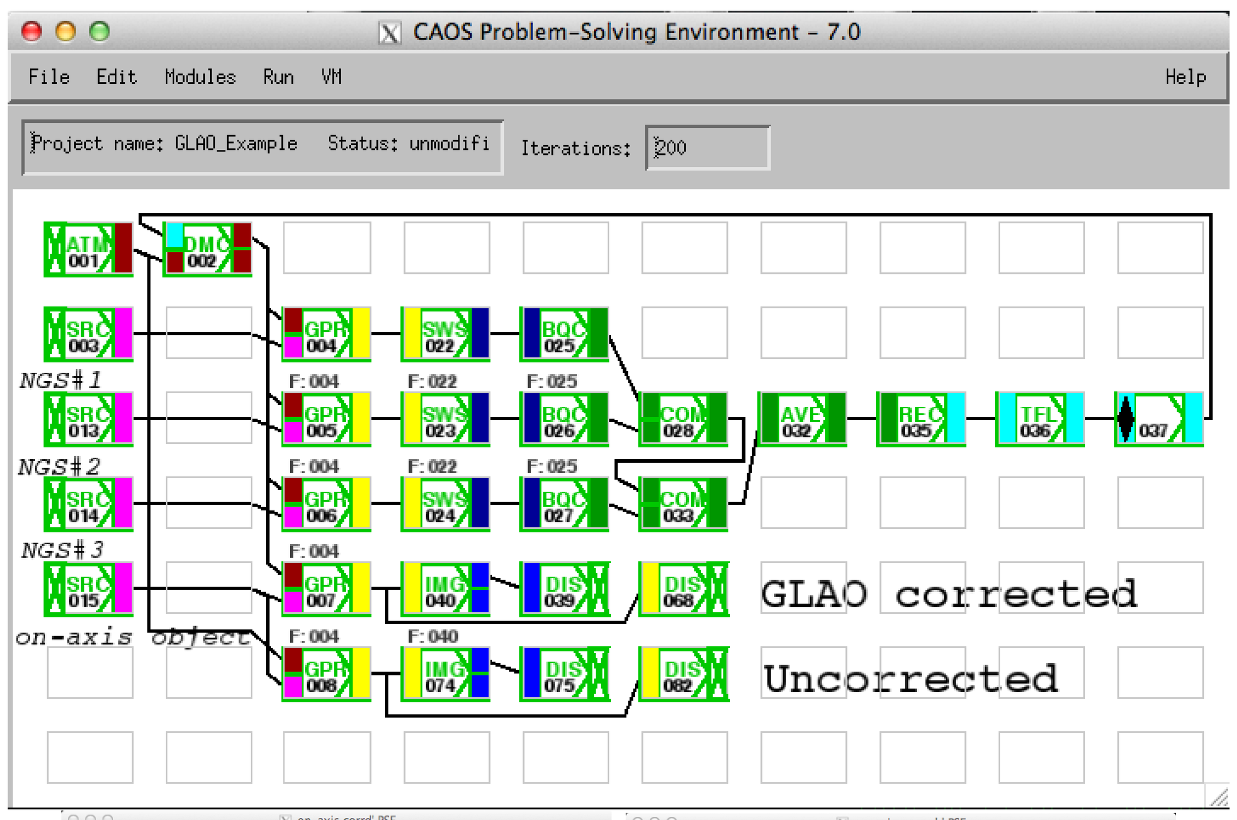
Module	Purpose
Optical turbulence & image formation	
ATM - ATMosphere building	-builds the turbulent atmosphere (FFT+subharmonics, Zernike) (see also utility PSG - Phase Screen Generation)
SRC - SouRCe definition	-characterizes the guide star/observed object
GPR - Geometrical PRopagator	-propagates light from source to telescope through atmosphere
IMG - IMaGing device	-forms an image of the observed object (+detector noises)
Wavefront sensing	
PYR - PYRamid wavefront sensor	-simulates the pyramid wavefront sensor
SLO - SLOpe computation	-computes the slopes from the pyramid signals
SWS - Shack-Hartman Wavefront Sensor	-simulates the Shack-Hartmann (SH) wavefront sensor
BQC - Barycentre/Quad-cell Centroiding	-compute the signals from the SH spots centroiding calculus
IWS - Ideal Wavefront Sensing	-applies "ideal" wavefront sensing (see text)
TCE - Tip-tilt CEntroiding	-computes and reconstructs tip-tilt
Wavefront reconstruction, control & correction	
REC - wavefront RECOnstruction	-reconstructs the wavefront
TFL - Time-FiLtering	-applies time-filtering after wavefront reconstruction
SSC - State-Space Control	-applies state-space control
DMI - Deformable MIrror	-simulates the behavior of a deformable mirror (DM)
TTM - Tip-Tilt Mirror	-simulates the behavior of a tip-tilt mirror
Calibration	
CFB - Calibration FiBer characterization	-defines a fiber to be used for calibration purpose
MDS - Mirror Deformation Sequencer	-generates a sequence of DM modes or influence functions
SCD - Save Calibration Data	-saves the calibration data (interaction matrix+set of deformates)
Wide-field AO	
AVE - signals AVEraging	-averages measurements from various wavefront sensors
COM - COMbine measurements	-combines measurements from various wavefront sensors
DMC - Deformable Mirror Conjugated	-corrects at different conjugated altitudes
Other modelling modules	
LAS - LASer characterization	-defines laser projector characteristics
NLS - Na-Layer Spot definition	-characterizes the Sodium-layer behavior
IBC - Interferometric Beam Combiner	-combines the light from two apertures
COR - COronagraphic module	-simulates various coronagraphs (Lyot, Roddier&Roddier, FQPM)
AIC - Achromatic Interfero-Coronagraph	-simulates the Achromatic Interfero-Coronagraph
BSP - Beam SPlitter	-splits the light beam
Other utility modules	
WFA - WaveFront Adding	-adds or combines together wavefronts
ATA - ATmosphere Adding	-adds or combines together atmospheres
IMA - IMage Adding	-adds or combines together images
STF - STructure Function	-calculates the structure function and compares to theory

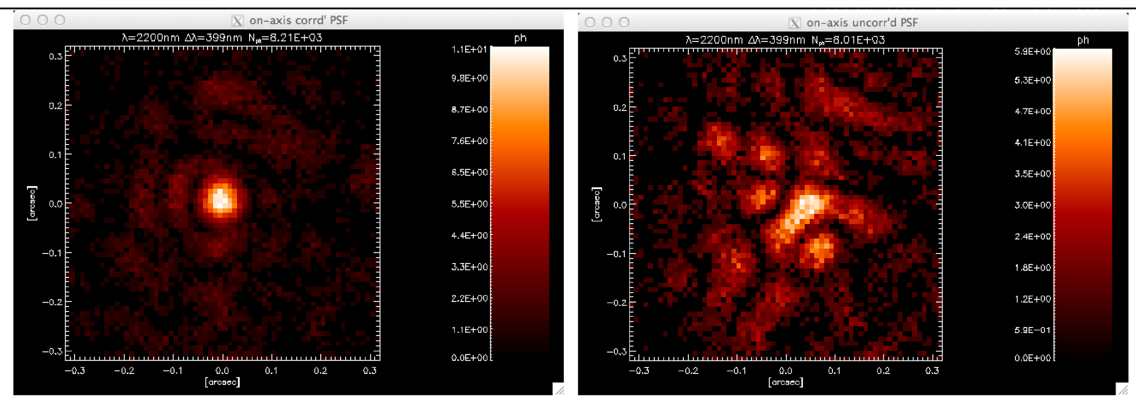
Wide-field AO modelling

The Software Package CAOS now permits in particular modelling of wide-field AO systems, thanks to three modules implemented for this version 7.0: COM, which combines measurements from different wavefront sensors, AVE, which averages these combined measurements, and DMC, which performs correction directly within the turbulent atmosphere (hence permitting correction at different altitudes for further MCAO simulations). As for real systems, a calibration procedure is needed in order to build the interaction matrix which will be pseudo-inverted at the beginning of the subsequent simulation phase. Such a calibration procedure is represented beside, where a series of mirror deformations (influence functions, Zernike polynomials, other modelled mirror deformations) are sensed by the wavefront sensor (here a SH modelled by SWS), and resulting signals stored in the interaction matrix are saved together with the DM deformates.



Beside, a representation of an actual simulation project modelling a ground-layer AO (GLAO) system. Here, an asterism of 3 natural guide stars (NGS) is used for wavefront sensing and the on-axis point-spread function is computed for sake of performance evaluation. Note that module GPR, which computes geometrical propagation of light from each star through the turbulent atmosphere (ATM) and to the one-only telescope is here cloned, i.e. its physical parameters are defined only once, as for module IMG which simulates an image-forming and detector device. Example of results obtained with and without GLAO correction at the center of the field is shown (8m-class telescope, 20″ field of view, band K, r_0=15 cm, three 8×8 SH sensors, 35 modes reconstructed).





Other new AO modelling capabilities

In addition to debugging and new features implemented within already existing modules and the wide-field modules seen before, other new modules are part of this distribution, such as IWS and SSC. The latter implements a digital state-space controller in the time domain and hence permits to use modern automatic control approaches. The performance of linear quadratic Gaussian (LGQ) control, which is the combination of the optimal state-feedback control of the DM and the optimal estimation of the atmospheric wavefront, can be evaluated [11].

The use of the SSC module is the same as for REC⊕TFL, with wavefront measures as inputs and commands for the DM as outputs. Module IWS permits to simulate an "ideal" wavefront sensor by projecting each propagated wavefront onto a basis of mirror deformations and giving as output the corrected wavefront, hence corresponding to fitting error alone.

Further developments

Other modules for wide-field AO modelling are under development, permitting the consideration of multiple sources and multiple sensors within single modules, and hence an easier modelling of GLAO systems, as well as layer-oriented and star-oriented MCAO systems. Another perspective regards the adaptation of the PAOLAC modules to both the last versions of the CAOS PSE and the PAOLA code. It will be included in a forthcoming version of the Software Package CAOS. Let us finally note that the whole tool is currently used for system studies and performance evaluation of the AO system CIAO (Calern Imaging Adaptive Observatory) to be mounted on one of the 1-m telescopes of C2PU (*Centre Pédagogique Planète et Univers* [12]) at Plateau de Calern near Nice (France), in both its standard AO mode and its wide-field (∼1′) planetary mode – the goal being to perform simulations in both semi-analytic and end-to-end flavors in a complementary manner.

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Freely download the CAOS PSE and the Software Package CAOS from lagrange.oca.eu/caos